

# SCIENTIFIC REPORTS

OPEN

## MoS<sub>2</sub>-Catalyzed transamidation reaction

Feng Zhang<sup>1</sup>, Lesong Li<sup>2</sup>, Juan Ma<sup>2</sup> & Hang Gong<sup>2</sup>

The MoS<sub>2</sub>-catalyzed transamidation reaction with high yields using *N,N*-dimethylformamide and other amides as carbonyl sources is developed here. The protocol is simple, does not require any additive such as acid, base, ligand, etc., and encompasses a broad substrate scope for primary, secondary and heterocyclic amines. Moreover, the acetylation and propanylation of amines also can be achieved with good to excellent yield by this strategy.

Transamidation reaction is very important in organic synthesis chemistry<sup>1–6</sup>. And the amide framework is widely applied in medicines<sup>7–10</sup>, natural products<sup>11</sup>, and functional materials (Fig. 1)<sup>12</sup>. Several organic small molecules have been served as carbonyl sources in transamidation reactions, including DMF/DMA<sup>13–24</sup>, formic acid/formate<sup>25–31</sup>, methanol<sup>32–36</sup>, ester<sup>37–41</sup>, and others<sup>42,43</sup>. Among them, DMF is well known as a cheap and readily available industrial organic solvent. Additionally, DMF has also been widely applied as a source of dimethylamino, formyl, carbonyl, –CONMe<sub>2</sub>, and methyl<sup>44–48</sup>.

The catalyzed transamidation reactions using DMF as carbonyl source have been reported. Various catalysts, including metal catalysts, such as Ni<sup>13</sup>, Ce<sup>14</sup>, Fe<sup>15</sup>, Cu<sup>16</sup>, L-Proline<sup>17</sup>, Pd<sup>49</sup> and metal-free catalysts, such as boronic acid<sup>18</sup> and their derivatives<sup>19,20</sup>, and imidazole<sup>50</sup> and its derivatives<sup>21</sup> have been succeed in this transformation. However, these strategies are often suffered from drawbacks such as use of unready available and costly catalysts, large amount of catalyst, essential additives, limited scope, and etc.

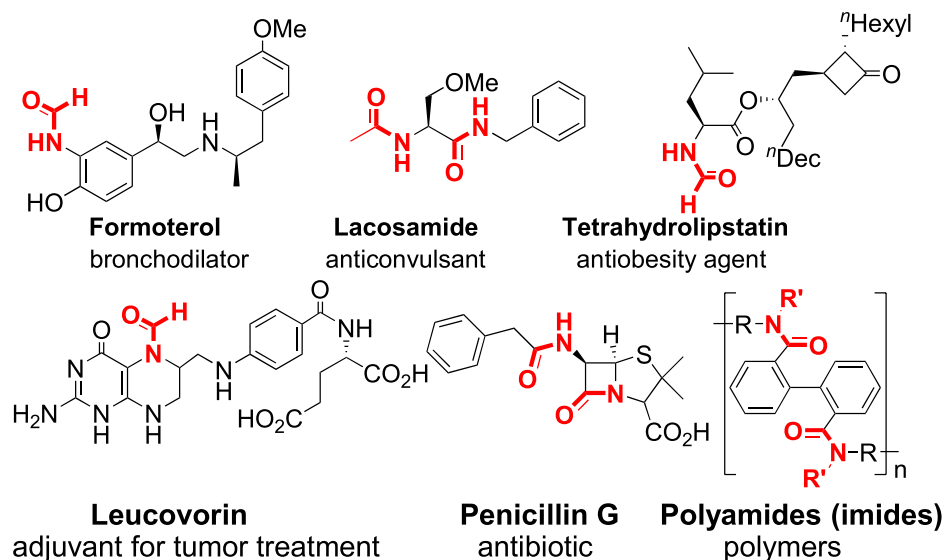
Herein, a highly efficient MoS<sub>2</sub>-catalyzed transamidation reaction using DMF and other amides as carbonyl sources has been developed (Fig. 2). This method has advantages such as using inexpensive catalyst and reagents, no need for any other additives. Moreover, this strategy has a broad substrate scope that both primary and secondary amines with different groups are suitable for this reaction and good to excellent yields can be achieved. Particularly, acetylation and propanylation reaction using the corresponding amides as reagents could be achieved with almost the same good results as formylation reaction.

### Results and Discussion

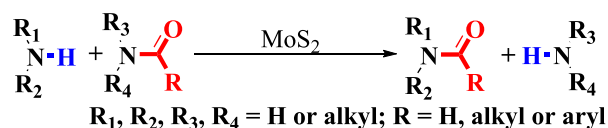
Initially, the transamidation of tetrahydroisoquinoline and DMF catalyzed by MoS<sub>2</sub> was investigated as the model reaction (Fig. 3). Various reaction conditions were optimized, such as catalyst, temperature, reaction time, and atmosphere. The results showed the yield of desired product is very poor in the absence of Mo catalyst (entry 1). When MoS<sub>2</sub> (12.5 mol%) and (NH<sub>4</sub>)<sub>2</sub>MoO<sub>4</sub>·4H<sub>2</sub>O (12.5 mol%) were used as catalyst, an excellent yield of 99% and 97% can be obtained, respectively (entries 2 and 3). Afterward, other metal salts, such as Fe(OAc)<sub>2</sub>·4H<sub>2</sub>O, Mn(OAc)<sub>3</sub>·2H<sub>2</sub>O, Cu(OAc)<sub>2</sub>, and Ni(OAc)<sub>2</sub>·4H<sub>2</sub>O were investigated as catalysts. Satisfactory yields could also be achieved, but none of these catalyst worked better than MoS<sub>2</sub>. Therefore, MoS<sub>2</sub> was selected as the optimal catalyst (entries 5–8). This reaction can be completed within 18 hours (entries 1, 11–13). Decreasing the reaction temperature (entry 14) proved to be unfavorable to this transformation. Additionally, the presence of air was harmful to this reaction (entry 15). Finally, this reaction was conducted by using stoichiometric amounts of DMF (1.5 equiv.) as the reagent in another solvent, but only poor yield was obtained (entries 16–17).

With the optimized condition in hand, various amines, including primary, secondary and heterocyclic amines, were tested for this reaction (Fig. 4). The results indicated that tetrahydroisoquinoline or its analogs could be converted to desired product with good to excellent yields (2a–f). This reaction was tolerable for various functional groups such as methoxy, bromide, and nitro. Notably, the electron-withdrawing group is unfavorable to this reaction (2d), and a lower yield would be found. In the case of heterocyclic amines, this transformation proceeded well and the transamidation products were obtained with excellent yields (2g–h). Other secondary amines, either circular or linear amines, underwent this reaction smoothly with high yields in most cases (2i–o). Remarkably,

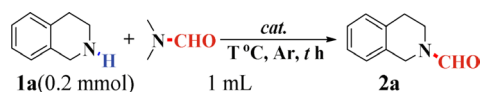
<sup>1</sup>College of Science, Hunan Agricultural University, Changsha, 410128, China. <sup>2</sup>The Key Laboratory of Environmentally Friendly Chemistry and Application of the Ministry of Education, College of Chemistry, Xiangtan University, Xiangtan, 411105, China. Correspondence and requests for materials should be addressed to F.Z. (email: [zhangf@iccas.ac.cn](mailto:zhangf@iccas.ac.cn)) or H.G. (email: [hgong@xtu.edu.cn](mailto:hgong@xtu.edu.cn))



**Figure 1.** Amide-containing biologically active molecules and polymer.

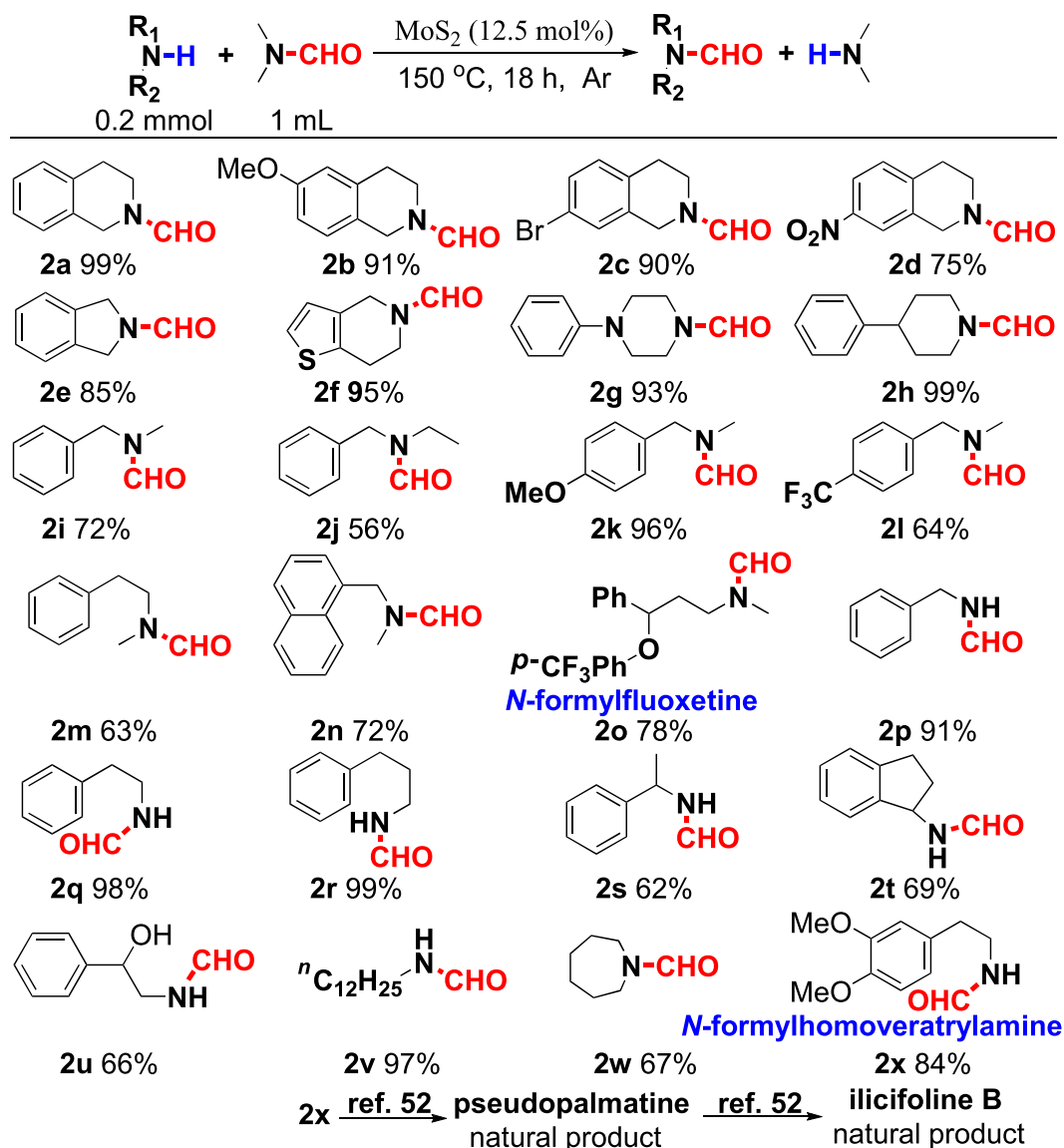


**Figure 2.** MoS<sub>2</sub>-catalyzed transamidation reaction.



Entry	Cat. (mol%)	t (h)	T (°C)	Yield (%) (2a:1a)
1	0	18	150	27/56
2	MoS <sub>2</sub> (12.5)	18	150	99/1
3	(NH <sub>4</sub> ) <sub>2</sub> MoO <sub>4</sub> ·4H <sub>2</sub> O (12.5)	18	150	97/1
4	MoO <sub>3</sub> (12.5)	18	150	89/10
5	Fe(OAc) <sub>2</sub> ·4H <sub>2</sub> O (12.5)	18	150	90/1
6	Mn(OAc) <sub>3</sub> ·2H <sub>2</sub> O (12.5)	18	150	86/0
7	Cu(OAc) <sub>2</sub> (12.5)	18	150	78/0
8	Ni(OAc) <sub>2</sub> ·4H <sub>2</sub> O (12.5)	18	150	92/1
9	MoS <sub>2</sub> (6)	18	150	82/14
10	MoS <sub>2</sub> (25)	18	150	98/0
11	MoS <sub>2</sub> (12.5)	3	150	42/43
12	MoS <sub>2</sub> (12.5)	6	150	64/36
13	MoS <sub>2</sub> (12.5)	12	150	94/0
14	MoS <sub>2</sub> (12.5)	18	130	59/31
15 <sup>b</sup>	MoS <sub>2</sub> (12.5)	18	150	49/53
16 <sup>c</sup>	MoS <sub>2</sub> (12.5)	18	150	12/67
17 <sup>d</sup>	MoS <sub>2</sub> (12.5)	18	150	13/71

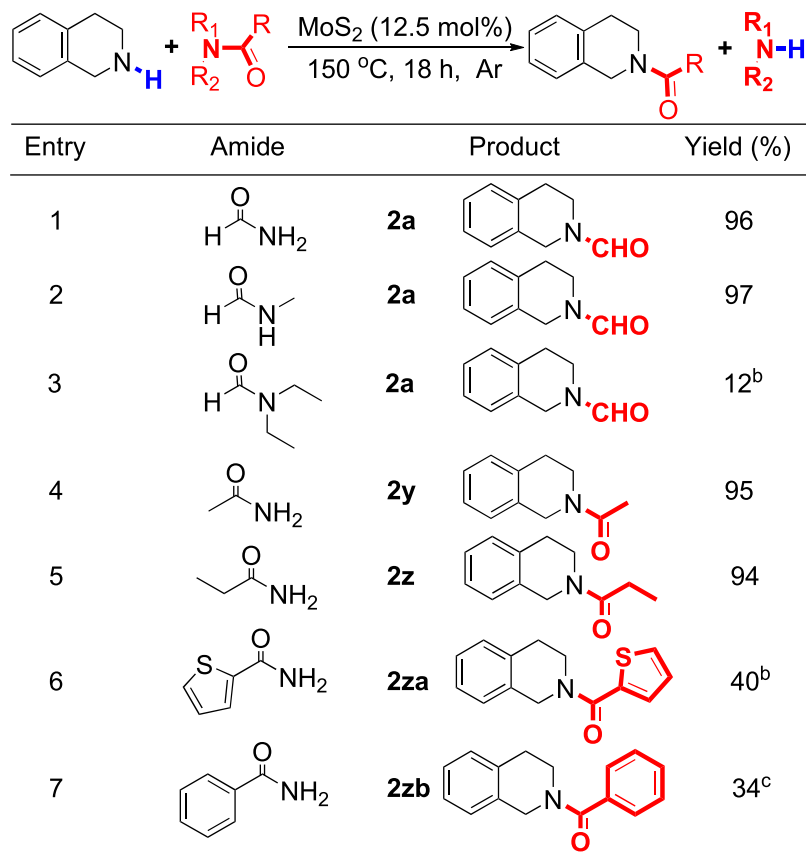
**Figure 3.** Selected optimization results. <sup>a</sup>Unless otherwise noted, all reactions were conducted at 0.2 mmol scale in a sealed tube in 1.0 mL DMF under argon atmosphere. Yields are detected by <sup>1</sup>H NMR using CH<sub>3</sub>NO<sub>2</sub> as internal standard; <sup>b</sup>Under air atmosphere; <sup>c</sup>1 mL toluene and 1.5 equiv. DMF were used; <sup>d</sup>1 mL dioxane and 1.5 equiv. DMF were used.



**Figure 4.** Substrate scope of amines. <sup>a</sup>Unless otherwise noted, all reactions were conducted on a 0.2 mmol scale, DMF (1.0 mL), MoS<sub>2</sub> (12.5 mol%) in a sealed tube under an atmosphere of argon for 18 h. Isolated yield was given.

compound **2o** which containing trifluoromethyl group, a marker for fluoxetine<sup>51</sup>, could be synthesized by this strategy with good yield (78%). However, the substrate with obvious steric hindrance group, such as ethyl (**1j**) on nitrogen was suffered from a reduced yield. This transamidation strategy was also applicable to primary amines, and good results as well as secondary amines were achieved (**2p–v**). Particularly, substrate containing hydroxyl group also converted to desired product with good yield (**2u**). The transamidation reaction and the corresponding product are valuable in organic synthesis reaction. For example, the natural product homoveratrylamine (**1x**) can be modified with formyl group by this strategy, and the corresponding product **2x** could be converted to a series of natural compounds such as pseudopalmatine, 8-oxopseudopalmatine, and ilicifoline B<sup>52</sup>. However, when aromatic amines such as aniline, tetrahydroquinoline and tetrahydroindole were used as substrates, only trace amount of desired products could be detected.

After the expanded substrate scope of amines, we then considered other appropriate carbonyl sources except DMF (Fig. 5). The results showed this reaction could also be proceeded with excellent yield by using formamide or *N*-methylformamide as formyl sources (entries 1–2). However, in the case of using sterically hindered amide such as *N,N*-diethylformamide as substrate, the yield would be reduced seriously (entry 3). Delightedly, acetamide and propionamide could be applied as carbonyl sources, and the corresponding *N*-acetylation and *N*-propionylation reaction were achieved with excellent yields (entries 4–5). These results further confirmed the transamidation strategy developed by us has a broad scope and is valuable. Moreover, in the case of aromatic amides used as carbonyl sources, a yield of 30~40% still could be found (entries 6–7).



**Figure 5.** Substrate scope of amides. <sup>a</sup>Unless otherwise noted, all reactions were conducted on a 0.2 mmol scale in a sealed tube in 1.0 mL amide under an atmosphere of argon for 18 h. Isolated yield was given; <sup>b</sup>Yield is detected by <sup>1</sup>H NMR using CH<sub>3</sub>NO<sub>2</sub> as internal standard; <sup>c</sup>From 2-thiophenecarboxamide 0.5 g, ethylene glycol 0.5 mL, reaction time is 24 h; <sup>d</sup>From benzamide 0.5 g, ethylene glycol 0.5 mL, reaction time is 24 h.

To verification the practicability of this strategy, the *N*-acetylation and *N*-propionylation reaction were expanded (Fig. 6). Either primary amines or secondary amines were converted to corresponding products with good to excellent yields (**2zc-zl**).

Significantly, the gram-scale synthesis of **2g** using only 3 mol% MoS<sub>2</sub> as catalyst was proceeded (Fig. 7A), and an excellent yield of 93% was obtained with an extended reaction time (4 days). Subsequently, the radical blocking experiments were performed using 1 equiv butylated hydroxytoluene (BHT), quinone, or 1,1-diphenylethane as a blocker, and the transamidation products were achieved with 80%, 83%, and 82% yield, respectively (Fig. 7B). These results indicated that this process is not a radical reaction, but a nucleophilic reaction.

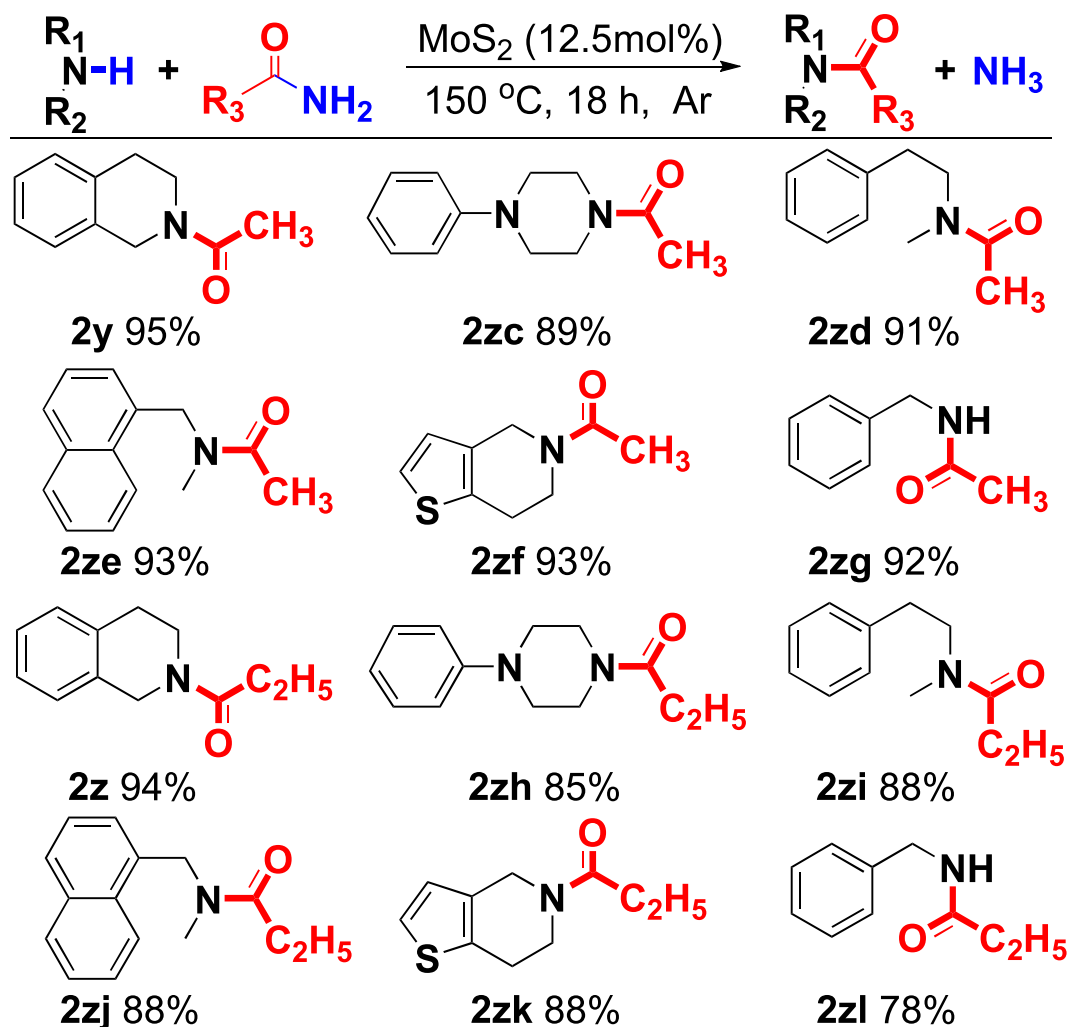
Based on the radical blocking experiments and previous reported metal-catalyzed transamidation reactions<sup>13–15</sup>, the reaction mechanism was proposed (Fig. 8). First, MoS<sub>2</sub> coordinated with DMF, and the carbonyl group is activated. Then, substrate amine acting as a nucleophilic reagent attacks the carbonyl group of the activated DMF. Subsequently, a tetrahedral intermediate (**I**) is generated. And then, the sterically congested intermediate (**I**) is disintegrated with a proton transfer, and intermediate **II** is formed. Finally, a ligand exchange reaction occurs between intermediate **II** and DMF to release the target molecule (T.M.).

## Conclusions

In summary, an efficient MoS<sub>2</sub>-catalyzed transamidation reaction using amides as carbonyl sources was reported. The advantages of this reaction are the readily available and inexpensive metal applied as catalyst, cheap amides applied as carbonyl source, scalable, broad scopes, free of any additives such as acid, base, ligand, and etc.

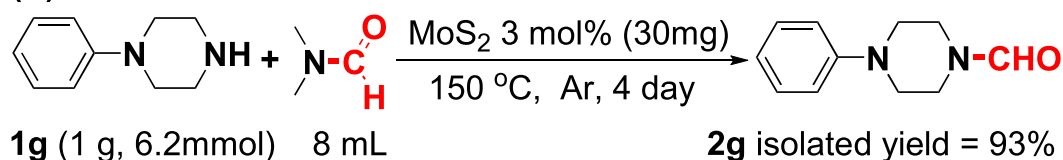
## Materials and Methods

**General Information.** The prepared thin-layer chromatography (Prep TLC) was performed for product purification using Sorbent Silica Gel 60 F254 TLC plates and visualized with ultraviolet light. IR spectra were recorded on a new Fourier transform infrared spectroscopy. <sup>1</sup>H, <sup>13</sup>C and <sup>19</sup>F NMR spectra were recorded on 400, 100, 377 MHz NMR spectrometer using CDCl<sub>3</sub> as solvent unless otherwise stated. HRMS were made by means of ESI. Melting points were measured on micro melting point apparatus and uncorrected. Unless otherwise noted, all reagents were weighed and handled in the air, and all reactions were carried out in a sealed tube under an atmosphere of argon. Unless otherwise noted, all reagents were purchased from reagent company, and used without further purifications. Notably, the powder MoS<sub>2</sub> were used in this work.

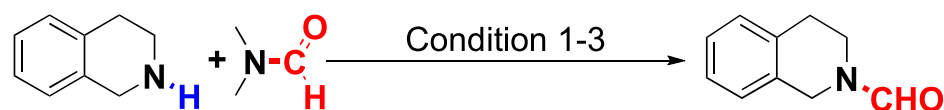


**Figure 6.** Substrate scope of acetylation and propylation of amines. <sup>a</sup>Unless otherwise noted, all reactions were conducted on a 0.2 mmol scale, acetamide or propionamide (1.0 g), MoS<sub>2</sub> (12.5 mol%) in a sealed tube under an atmosphere of argon for 18 h. Isolated yield was given.

**(A) Gram scale reaction:**

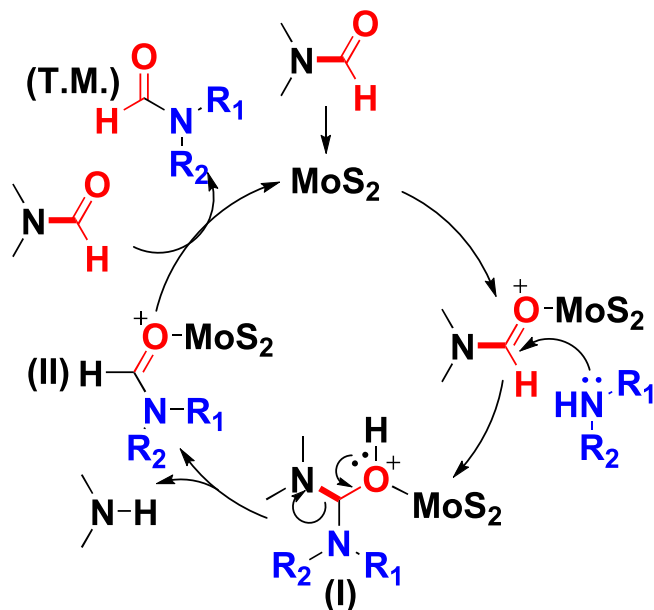


**(B) Radical inhibition experiments:**



Condition 1: Standard reaction conditions, BHT 1 equiv, yield 80%;  
 Condition 2: Standard reaction conditions, quinone 1 equiv, yield 83%;  
 Condition 3: Standard reaction conditions, 1,1-diphenylethene 1 equiv, yield 82%.

**Figure 7.** Gram reaction of 1g and radical blocking experiments of 1a.



**Figure 8.** Proposed mechanism for transamidation using MoS<sub>2</sub> as catalyst.

**Experimental Section.** A typical experimental procedure for transamidation was conducted as follows: A solution of amine (0.2 mmol), MoS<sub>2</sub> (12.5 mol%, 4 mg) in DMF (1.0 mL) was stirred in a sealed tube under an atmosphere of argon at 150 °C for 18 h. After being cooled to room temperature, the reaction mixture was filtered, washed with ethyl acetate (20 mL). Afterward, the solution was added 10 mL water and extracted with ethyl acetate (3 × 15 mL), and then the combined organic layers were dried with Na<sub>2</sub>SO<sub>4</sub>. The solvent was evaporated under vacuum and the crude product was purified by Prep TLC on silica gel with petroleum ether and ethyl acetate to obtain the pure product.

## References

- Pattabiraman, V. R. & Bode, J. W. Rethinking amide bond synthesis. *Nature* **480**, 471–479 (2011).
- Lundberg, H., Tinnis, F., Selander, N. & Adolffsson, H. Catalytic amide formation from non-activated carboxylic acids and amines. *Chem. Soc. Rev.* **43**, 2714–2742 (2014).
- Humphrey, J. M. & Chamberlin, A. R. Chemical synthesis of natural product peptides: coupling methods for the incorporation of noncoded amino acids into peptides. *Chem. Rev.* **97**, 2243–2266 (1997).
- Cupido, T., Tulla-Puche, J., Spengler, J. & Albericio, F. The synthesis of naturally occurring peptides and their analogs. *Curr. Opin. Drug Disc.* **10**, 768–783 (2007).
- Deming, T. J. Synthetic polypeptides for biomedical applications. *Prog. Polym. Sci.* **32**, 858–875 (2007).
- Chen, B. C. *et al.* A new facile method for the synthesis of 1-arylimidazole-5-carboxylates. *Tetrahedron Lett.* **41**, 5453–5456 (2000).
- Hett, R., Fang, Q. K., Gao, Y., Wald, S. A. & Senanayake, C. H. Large-scale synthesis of enantio- and diastereomerically pure (R,R)-formoterol. *Org. Process Res. Dev.* **2**, 96–99 (1998).
- Choi, D., Stables, J. P. & Kohn, H. Synthesis and anticonvulsant activities of *N*-benzyl-2-acetamidopropionamide derivatives. *J. Med. Chem.* **39**, 1907–1916 (1996).
- Ma, G. *et al.* Total synthesis and comparative analysis of orlistat, valilactone, and a transposed orlistat derivative: inhibitors of fatty acid synthase. *Org. Lett.* **8**, 4497–4500 (2006).
- Forsch, R. A. & Rosowsky, A. A new one-step synthesis of leucovorin from folic acid and of 5-formyl-5,6,7,8-tetrahydrohomofolic acid from homofolic acid using dimethylamine-borane in formic acid. *J. Org. Chem.* **50**, 2582–2583 (1985).
- Batchelor, F. R., Doyle, F. P., Nayler, J. H. C. & Rolinson, G. N. Synthesis of penicillin: 6-aminopenicillanic acid in penicillin fermentations. *Nature* **183**, 257–258 (1959).
- Ghosh, M. K. & Mittal, K. L. *Polyimides fundamentals and applications*. Marcel Dekker: New York (1996).
- Sonawane, R. B., Rasal, N. K. & Jagtap, S. V. Nickel-(II)-catalyzed *N*-formylation and *N*-acylation of amines. *Org. Lett.* **19**, 2078–2081 (2017).
- Wang, Y. H. *et al.* Transformylating amine with DMF to formamide over CeO<sub>2</sub> catalyst. *Chem. Commun.* **50**, 2438–2441 (2014).
- Thale, P. B., Borase, P. N. & Shankarling, G. S. Transamidation catalysed by a magnetically separable Fe<sub>3</sub>O<sub>4</sub> nano catalyst under solvent-free conditions. *RSC Adv.* **6**, 52724–52728 (2016).
- Zhang, M. *et al.* Efficient copper(II)-catalyzed transamidation of non-Activated primary carboxamides and ureas with amines. *Angew. Chem. Int. Ed.* **124**, 3971–3975 (2012).
- Rao, S. N., Mohan, D. C. & Adimurthy, S. L-proline: an efficient catalyst for transamidation of carboxamides with amines. *Org. Lett.* **15**, 1496–1499 (2013).
- Nguyen, T. B., Sorres, J., Tran, M. Q., Ermolenko, L. & Al-Mourabit, A. Boric acid: a highly efficient catalyst for transamidation of carboxamides with amines. *Org. Lett.* **14**, 3202–3205 (2012).
- El Dine, T. M., Evans, D., Rouden, J. & Blanchet, J. Formamide synthesis through borinic acid catalysed transamidation under mild conditions. *Chem. Eur. J.* **22**, 5894–5898 (2016).
- Lanigan, R. M., Starkov, P. & Sheppard, T. D. Direct synthesis of amides from carboxylic acids and amines using B(OCH<sub>2</sub>CF<sub>3</sub>)<sub>3</sub>. *J. Org. Chem.* **78**, 4512–4523 (2013).
- Chikkulapalli, A. *et al.* Convenient *N*-acetylation of amines in *N,N*-dimethylacetamide with *N,N*-carbonyldiimidazole. *Tetrahedron Lett.* **56**, 3799–3803 (2015).
- Wang, Y. H. *et al.* C-N and N-H bond metathesis reactions mediated by carbon dioxide. *ChemSusChem* **8**, 2066–2072 (2015).



23. Zhang, Q. & Chen, C. Direct acylation of aryl amines using dimethylformamide and dimethylacetamide as the acyl resources. *J. Saudi. Chem. Soc.* **20**, 114–119 (2016).
24. Becerra-Figueroa, L., Ojeda-Porras, A. & Gamba-Sánchez, D. Transamidation of carboxamides catalyzed by Fe(III) and water. *J. Org. Chem.* **79**, 4544–4552 (2014).
25. Hosseini-Sarvari, M. & Sharghi, H. ZnO as a new catalyst for *N*-formylation of amines under solvent-free conditions. *J. Org. Chem.* **71**, 6652–6654 (2006).
26. Chen, Z. K. *et al.* An eco-benign and highly efficient procedure for *N*-acylation catalyzed by heteropolyanion-based ionic liquids using carboxylic acid under solvent-free conditions. *Tetrahedron* **70**, 2237–2245 (2014).
27. Das, B., Krishnaiah, M., Balasubramanyam, P., Veeranjanyulu, B. & Nandankumar, D. A remarkably simple *N*-formylation of anilines using polyethylene glycol. *Tetrahedron Lett.* **49**, 2225–2227 (2008).
28. Brahmachari, G. & Laskar, S. A very simple and highly efficient procedure for *N*-formylation of primary and secondary amines at room temperature under solvent-free conditions. *Tetrahedron Lett.* **51**, 2319–2322 (2010).
29. Alewi, B. A., Mitachi, K. & Kurosu, M. Mild and convenient *N*-formylation protocol in water-containing solvents. *Tetrahedron Lett.* **54**, 2077–2081 (2013).
30. Rahman, M., Kundu, D., Hajra, A. & Majee, A. Formylation without catalyst and solvent at 80 °C. *Tetrahedron Lett.* **51**, 2896–2899 (2010).
31. Ganapati Reddy, P., Kishorekumar, G. D. & Baskaran, S. A convenient method for the *N*-formylation of secondary amines and anilines using ammonium formate. *Tetrahedron Lett.* **41**, 9149–9151 (2000).
32. Chakraborty, S. *et al.* Manganese-catalyzed *N*-formylation of amines by methanol liberating H<sub>2</sub>: a catalytic and mechanistic study. *Angew. Chem. Int. Ed.* **129**, 4293–4297 (2017).
33. Kang, B. & Hong, S. H. Hydrogen acceptor- and base-free *N*-formylation of nitriles and amines using methanol as C<sub>1</sub> source. *Adv. Synth. Catal.* **357**, 834–840 (2015).
34. Ortega, N., Richter, C. & Glorius, F. *N*-formylation of amines by methanol activation. *Org. Lett.* **15**, 1776–1779 (2013).
35. Tanaka, S. *et al.* Selective aerobic oxidation of methanol in the coexistence of amines by nanoporous gold catalysts: highly efficient synthesis of formamides. *Chem. Eur. J.* **19**, 11832–11836 (2013).
36. Xu, B. J., Madix, R. J. & Friend, C. M. Dual-function of alcohols in gold-mediated selective coupling of amines and alcohols. *Chem. Eur. J.* **18**, 2313–2318 (2012).
37. Hie, L. *et al.* Nickel-catalyzed activation of acyl C–O bonds of methyl esters. *Angew. Chem. Int. Ed.* **128**, 2860–2864 (2016).
38. Sharley, D. D. S. & Williams, J. M. J. Acetic acid as a catalyst for the *N*-acylation of amines using esters as the acyl source. *Chem. Commun.* **53**, 2020–2023 (2017).
39. Gnanaprakasam, B. & Milstein, D. Synthesis of amides from esters and amines with liberation of H<sub>2</sub> under neutral conditions. *J. Am. Chem. Soc.* **133**, 1682–1685 (2011).
40. Muñoz, J. D. M., Alcázar, J., Hoz, A. D. L., Díaz-Ortizb, Á. & Diego, S. A. A. D. Preparation of amides mediated by isopropylmagnesium chloride under continuous flow conditions. *Green Chem.* **14**, 1335–1341 (2012).
41. Ohshima, T. *et al.* Sodium methoxide: a simple but highly efficient catalyst for the direct amidation of esters. *Chem. Commun.* **48**, 5434–5436 (2012).
42. Zhang, L., Han, Z., Zhao, X. Y., Wang, Z. & Ding, K. Highly efficient ruthenium-catalyzed *N*-formylation of amines with H<sub>2</sub> and CO<sub>2</sub>. *Angew. Chem. Int. Ed.* **127**, 6284–6287 (2015).
43. Das, S., Bobbink, F. D., Bulut, S., Soudani, M. & Dyson, P. J. Thiazolium carbene catalysts for the fixation of CO<sub>2</sub> onto amines. *Chem. Commun.* **52**, 2497–2500 (2016).
44. Ding, S. T. & Jiao, N. *N,N*-dimethylformamide: a multipurpose building block. *Angew. Chem. Int. Ed.* **51**, 9226–9237 (2012).
45. Muzart, J. *N,N*-dimethylformamide: much more than a solvent. *Tetrahedron* **65**, 8313–8323 (2009).
46. Ohtaki, H. Structural studies on solvation and complexation of metal ions in nonaqueous solutions. *Pure Appl. Chem.* **59**, 1143–1150 (1987).
47. Kobayashi, S., Sugiura, M. & Ogawa, C. Neutral coordinate-organocatalysts in organic synthesis: allylation of acylhydrazones with allyltrichlorosilanes. *Adv. Synth. Catal.* **346**, 1023–1034 (2004).
48. Pastoriza-Santos, I. & Liz-Marzan, L. M. *N,N*-dimethylformamide as a reaction medium for metal nanoparticle synthesis. *Adv. Funct. Mater.* **19**, 679–688 (2009).
49. Meng, G. R., Lei, P. & Szostak, M. A general method for two-step transamidation of secondary amides using commercially available, air- and moisture-stable palladium/NHC (*N*-heterocyclic carbene) complexes. *Org. Lett.* **19**, 2158–2161 (2017).
50. Suchy, M., Elmehriki, A. A. H. & Hudson, R. H. E. A remarkably simple protocol for the *N*-formylation of amino acid esters and primary amines. *Org. Lett.* **13**, 3952–3955 (2011).
51. Wirth, D. D. *et al.* Maillard reaction of lactose and fluoxetine hydrochloride, a secondary amine. *J. Pharm. Sci.* **87**, 31–39 (1998).
52. Stubba, D. *et al.* Xylochemistry-making natural products entirely from wood. *Angew. Chem. Int. Ed.* **54**, 14187–14189 (2015).

## Acknowledgements

We are grateful to the National Natural Science Foundation of Hunan Province (No. 2018JJ2389), National Natural Science Foundation of China (No. 21402168), Hunan 2011 Collaborative Innovation Center of Chemical Engineering & Technology with Environmental Benignity and Effective Resource Utilization and the Project of Innovation Team of the Ministry of Education (IRT\_17R90) for their support of our research.

## Author Contributions

Conceived and designed the experiments: L.L. and J.M. performed the experiments. H.G. and F.Z. supervised all research. H.G. also wrote the manuscript. All authors contributed to reagents/materials/technical support to this study.

## Additional Information

**Supplementary information** accompanies this paper at <https://doi.org/10.1038/s41598-019-39210-5>.

**Competing Interests:** The authors declare no competing interests.

**Publisher's note:** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.



**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/>.

© The Author(s) 2019